1969 ~~USDA~~ FOREST SERVICE RESEARCH PAPER RM-51



# REVIEW AND COMPARISON OF SITE EVALUATION METHODS

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USDA Forest Service
Research Paper RM-51

1969

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# Review and Comparison of Site Evaluation Methods

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This review does not attempt to include every paper or recognize every school of site evaluation. The field was first outlined and then developed. The papers cited were selected mainly to illustrate concepts, methods, and results. For example, the principles of characterizing site by classifying the vegetation are covered by discussing the Finnish and related work. The Zurich-Montpellier and Russian schools are regarded as other means of classifying vegetation and are not discussed here, although work by their adherents is cited in other contexts. Emphasis has been on North American work, on European work that has been especially influential in North America, and on certain European work that provided insight into North American work.

The review is organized into three main sections, each followed by a summary. They are:

1. The site index approach.
2. Vegetation approaches.
3. Environmental approaches.

Some studies have combined approaches. These are discussed where they contribute to the development of the subject.

## The Site Index Approach

A common method of evaluating site in even-aged forests or those with an even-aged overstory has been site index—the average height of sample canopy trees at a selected index age, such as 50 years.

A stand of index age is seldom encountered. Assume a stand younger than the index age. What is its site index? That is, how tall will it be when it reaches the index age? To estimate site index, the age of the stand and the average height of several dominant trees are determined. In some early systems, the average of a sample from both the dominant and codominant crown classes was used—for example, that of McArdle (1930) for Douglas-fir[2] in the Pacific Northwest. The point at which the age and height ordinates intersect are found on a graph, and the site index value estimated by interpolation between two site index curves. The procedure is the same for stands older than the index age. Figure 1 shows site index curves for Engelmann spruce (Alexander 1967).

Site index curves describe the course of height growth of hypothetical trees of specified site indexes. Sometimes height-age tables designed from site index curves are used instead of the curves themselves.

According to Cajander (1926), Huber used site index in Germany as early as 1824. Its use spread

[2]*Common and scientific names of plants, insects, and diseases mentioned are listed on p. 27.*

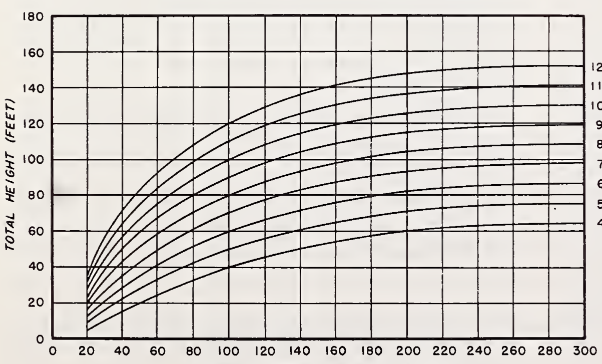


*Figure 1.-Engelmann spruce site index curves for the central Rocky Mountains (Alexander 1967).*

to Scandinavia (Jonson 1914) and to the United States (Sterrett 1914). Not long after its introduction into the United States, the concept was discussed in a series of articles (Parker 1916, Roth 1916, 1918, Spring 1917, Watson 1917, Bates 1918, especially Frothingham 1918), and compared with the volume-age relationship, vegetation types, and environmental factors as possible alternative indexes. The height-age relationship was deemed much superior.

Site index curves can be developed from height growth records from permanent plots, where these are available (Spurr 1952, 1956). Mostly, however, they are based on the heights and ages of stands on many temporary sample plots. The range of age classes and of sites must be included in the sample. This is the approach described in American texts on forest mensuration from Chapman (1921) to Husch (1963).

For years the standard methods of curve construction in the United States were graphical anamorphosis as described by Bruce (1926), or the graphical method of Osborne and Schumacher (1935). In recent years the multiple regression of height on age and on site index has been used. The general procedure is similar to the earlier standard graphical methods except that the curve form is dictated by a selected equation form, and the curves are fitted by the method of least squares.

Construction of a set of site index curves by the above methods assumes that (1) all the factor combinations sampled produced height-age curves which are harmonic, that is, which are proportioned to each other throughout the ages of the stands, and (2) the site index given by any stand will not change during the life of that stand. Weaknesses in these assumptions have been discussed by Cajander (1926), Bull (1931), Spurr (1952,1956), Carmean (1956), and Vincent (1961).

Errors from the first assumption should be reduced by the use of "natural" site index curves. According to their description by Cajander (1926), the pioneering curves of Huber were natural site index curves. Bull (1931) introduced them to the United States, and their principle is well illustrated in the construction of his site index curves for planted red pine in Connecticut. He described the actual course of height growth for each sample tree by measuring the height of each annual branch whorl. The height-age data for all trees in a single site index class were then combined to form a site index curve for that class. No curve depended on data from any other class.

The same principle has been followed where whorl counts are not possible; basic data are ring counts at measured intervals along the boles of felled trees—that is "stem analysis." This was Huber's method (Cajander 1926). Jameson (1965) illustrated serious discrepancies between standard site index curves for jack pine in Saskatchewan and height-age curves based on stem analysis.

The advantage of natural site index curves is limited, however, because among plots with virtually identical heights at index age, tree curves on one plot may differ considerably from tree curves on another plot, at least for aspen in the Rocky Mountains (Jones 1967a), lodgepole pine,[3] and for birch in Norway (Persson 1959). This diversity of curve forms for plots of similar height at index age results in a plot giving different estimates of site index at different ages, regardless of whether the class curve is "natural" or derived by standard anamorphic techniques.

Williamson (1963) demonstrated moderate site index changes in 30- to 50-year height records on Douglas-fir growth plots. Watt (1960) found only unimportant changes in site index on western white pine plots.

Diversity in the forms of height growth curves presumably is caused by different combinations of site factors and changes in the identity of limiting factors during stand development. These changes may result, for example, in rapid juvenile growth and early growth deterioration on some sites, while on others juvenile growth may be moderate but may slow little at maturity. Genetic differences undoubtedly contribute in some degree to curve-form diversity in most if not all species. Contrasting habitats select for populations that will differ genetically according to the type and severity of selection and the nature of the response mechanism. In the case of bigtooth aspen, and of quaking aspen in the Rocky Mountains, genetic differences between clones are important (Zahner and Crawford 1965; Jones 1967b).

Ilvessalo (1927, 1937) presented height-age curves for Scots pine in Finland, for different site-types as defined by ground vegetation. The curve forms differed, sometimes considerably, on different site types. The same was true for ponderosa pine on different site types in the northern Rocky Moun-

[3] *Unpublished data on file in the spruce-fir and lodgepole pine project, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.*

tains (Daubenmire 1961). Carmean (1956) found that, forDouglas-fir on different soils in southwestern Washington, two stands with similar heights at index age 100 may have differed in height at age 20 by 2:1, the differences remaining very large even at age 50. As a result, site index estimates may err greatly.

Carmean (1956), Beck (1962), Zahner (1962), and Van Eck and Whiteside (1963) developed separate sets of site index curves for different soil or landform categories. This promises to reduce errors from both of the assumptions discussed: that height-age curves are harmonic and that site index remains constant as a stand ages. It actually amounts to superimposing a site index classification on an environmental classification—it could also be superimposed on a vegetational classification—and may be worthwhile where curve-form variability is sufficient.

Ward et al. (1965) suggested bypassing site index curves and formulas entirely by simply felling and sectioning sample trees on the site for which the index is desired. The site index is then read directly from the tree curves. This requires that the stand be at least as old as the index age, however, and is laborious and time consuming.

Juvenile growth rates are particularly apt to be poorly correlated with later growth rates and with site index. To reduce the effects, age is often based on the ring count at breast height, 4.5 feet, with or sometimes without (Jones 1966, Alexander 1967) the addition of the average number of years required by the species to reach 4.5 feet. In Denmark, age may be based on a count of rings as high as 2.3 meters (7.5 feet) above the ground (Løvengreen 1954). Walters et al. (1961) tried to refine this approach for some northwestern species by adding a variable number of years required to reach breast height, the number being based on crown class.

A mathematical approach to site index curve construction presented by Stage (1963) attempts to compensate for the effects of factors affecting seedlings and saplings. Ebeling (1959) was skeptical of highly refined systems of yield prediction, believing them more complicated than accurate.

A very basic assumption in site index is that height growth is not importantly influenced by stand density. Hopkins (1963), on the basis of a thinning study, pointed out that close spacing in young coastal Douglas-fir slowed height growth. In the northern Rocky Mountains, overstocking reduced the height growth of ponderosa pine enough that separate sets of site index curves have been made for different levels of stocking (Lynch 1958). The height growth of lodgepole pine in the Rocky Mountains is so strongly influenced by stocking over a wide range of densities (Smithers 1961, Holmes and Tackle 1962) that the height-age relationship alone is largely useless as an index of site. An extensive study has developed a system for this notoriously difficult species, incorporating height, age, and density (Alexander 1966, Alexander et al. 1967).

Some sites with similar height-growth potentials are very different from some others. In some cases they may differ appreciably in their stocking or longevity potentials, and therefore in their yield potential. This probably is not often an important factor, however, and seems to involve poor sites primarily.

Plantation cultivation may sometimes make a substantial difference in apparent site index (Wittenkamp and Wilde 1964). Correction factors may prove desirable where cultivation is planned.

For site index to give valid results, the site must bear an even-aged overstory where the heights of dominants have not been strongly influenced by stand history. For example, by partial cutting (Ilvessalo 1954) or by dwarf mistletoe infection (Shea 1964). Juvenile growth rates often are inconsistent with later rates. Therefore, young stands often give misleading estimates, and many site index curves are not even drawn below age 20. With some species, 20- or even 30-year-old stands give unreliable indexes (Warrack and Fraser 1955, Alexander 1966, Jones 1966).

For the above reasons or because of deforestation, many sites do not have stands suitable for determining site index. Also, the interest in yield potential is always related to a particular species. A site may be occupied by lodgepole pine, while the manager may wish to know its potential for Engelmann spruce. In some cases the site index for two species may be highly correlated (Doolittle 1958, Foster 1959, Olson and Della-Bianca 1959, Deitschman and Green 1965). Use of regressions to estimate the site index for one species from that for another seems risky, however, unless the regression is known to hold for the particular environmental combination involved.

The weaknesses in site index do not appear to be serious for most species in even-aged stands,

however. This is especially true if McGee and Clutter (1967) are right in stating that "there is seldom a need for site information that predicts future heights within ten feet" except for land acquisition and research purposes. In the United States, probably most foresters agree with Hodgkins (1956) and Vincent (1961) that site index is the best generally available indicator of relative yield potential where suitable stands are present. Certainly, site index often serves as the basic criterion in developing and testing alternative methods.

At the same time, site index is an index only to yield potential. It is not generally suited to other purposes—to characterizing sites for silvicultural prescription, for example. As an instance, one high index site may be readily reforested after fire or harvest, and another may be very difficult to reforest.

On the other hand, a habitat classification using an environmental approach has been developed for evaluating blister rust hazard to eastern white pine (Van Arsdel 1961). The susceptibility of subalpine fir to spruce budworm in the Canadian Rockies differed on different site-types as defined by ground vegetation (Shepherd 1959) as did ponderosa pine susceptibility to dwarf mistletoe in the northern Rockies (Daubenmire 1961). Comparable vegetation site-types have been widely used in prescribing forest regeneration methods in Europe (Kabzems 1951, Ilvessalo 1954, Arnborg 1960, Bärring 1965) and have been developed as a framework for general ecological studies in a section of the northern Rocky Mountains (Daubenmire 1952). The potential value of environmental site classification or ordination in studies of forest seed provenance and other studies of racial variation is clear from discussions by Dietrichson (1964), Callaham (1965), Silen (1965), and Benson et al. (1967).

Summarizing, even good site index curves used with proper regard for their limitations are a somewhat rough index to the productivity of sites. But it is the most direct method, and for most species in suitable stands, good site index curves probably are the best tool for evaluating productivity.

There remains a real need for the classification or ordination of sites based on environment or vegetation or both, not to replace the site index approach, but to supplement it and to some extent to refine it.

## Vegetation Approaches

Under vegetation approaches I am including what many writers term the ecosystem approach, if the vegetation is used to define the ecosystem. The primary difference between the vegetation approach of Cajander (1926) and the ecosystem approach of Krajina (1960), for example, is the degree of emphasis given the environment in deciding upon the defining vegetaion.

The vegetation approach may take the form of classification or ordination.

### Classification

Malmström (1949) cites two early Fennoscandian papers (Post 1862, Norrlin 1871) in which forest ecosystems were classified according to vegetation but with the explicit consideration of the habitats.

The approach received wide attention after Cajander (1909, 1926) subdivided the forest habitats of Finland into a complete set of forest site-types.[4] Each site-type was defined by the climax ground vegetation, using the polyclimax concept. Environmental similarity was a criterion in defining the site-types (Cajander 1926, Kalela 1960) and it was assumed that for forestry purposes all habitats falling within a single site-type could be considered effectively uniform.

By means of growth studies, yield prediction tables were developed for the different site-types (Ilvessalo 1927, 1937, Carbonnier 1954), and site-types have provided the frame of reference for forest management and research in Finland for many years (Ilvessalo 1954, Högnäs 1966, p. 94).

Coile (1938), an advocate of the soils approach to site evaluation, questioned whether the climax vegetation could be recognized after severe disturbance, and whether shallow-rooted ground vegetation would reflect the deeper lying soil conditions encountered by tree roots. Ilvessalo (1954) and Kujala

[4] *The Finnish "metsätyyppi," Swedish "skogstyp," and German "Waldtyp" translate literally to "forest type." In the American literature, however, the term forest type is widely used as a synonym of "forest cover type," referring to the composition of the forest canopy. To avoid confusion, the term "forest site-type" is often used to signify Waldtyp and will be used here.*

(1960) have claimed that those criticisms are unimportant. Ilvessalo (1954) admitted that mistakes can be made in assigning land to a site-type, but that misassignments are usually of borderline cases into a site-type similar to the correct one. Kujala (1960) pointed out that the advantage of deep-lying nutrient-rich layers are reflected in the ground vegetation through the fertilizing effect of leaf litter.

More to the point are the reactions of those who have tried to apply site-types. Viro (1961), himself a Finn, stated that the use of ground vegetation to evaluate productivity "is almost confined to Finland; elsewhere it has not been found to give a correct picture of site fertility." Another Finn, Högnäs (1966, pp.94-95), stated that dominant height and age are necessary for practical site quality classification on Finland's Ahvenanmaa (Åland) Archipelago. He ascribed this to the influence of parent materials and the maritimity of the climate, some of the former atypical and the latter completely outside the range of Finnish mainland conditions.

Operational systems of site-types have been developed and tried in Sweden (Eneroth 1931, reviewed by Malmström 1949, Malmström 1949, Arnborg 1953). Site index, however, remains the standard means of estimating productivity there (Carbonnier 1954); site-types are used as a frame of reference for silvicultural prescription (Malmström 1949, Tamm 1950, Arnborg 1960). The Swedish conclusion has been that site-types in Sweden include too much growth variability. In explanation it has been suggested that growth is more sensitive than vegetation composition to differences in elevation, slope direction, and past stand treatment (Malmström 1949, p. 116, Arnborg 1960). Sweden generally has considerably greater elevation contrasts than Finland.

In Latvia the site-type concept was used to classify forest land, with very explicit attention being given to soil profile, stand structure, secondary successions, and forest regeneration in delineating vegetation site-types. These thorough ecosystem studies were considered necessary because the Latvian flora is richer and the soils characteristically deeper and more complex than those of Finland. The resulting site-types were the basis of management on 5 million acres of state and private forests in prewar Latvia (Kabzems 1951).

Interest in site-types has been shown by at least two directors of federal forestry research in Canada, J. D. B. Harrison (1955) and D. R. Redmond (1964). Because of Canada's size and climatic diversity, the government has published a complete geographic classification of the country into forest regions and sections. It is based on community-habitat relations, and reflects differences in climate and physiography (Halliday 1937, revised by Rowe 1959). This Canada-wide classification serves as a framework for development of sectional classifications of habitats based either on vegetation or environment. Classifications based on vegetation have been made for several sections (Linteau 1955, Lemieux 1963, Damman 1964, Mueller-Dombois 1964) and for independently delineated but more or less comparable areas (Illingworth and Arlidge 1960, Loucks 1962a, Wilton 1964).

Krajina (1963, 1964, 1965) and his students have made a number of detailed ecological studies apparently aimed at the eventual classification of the ecosystems of British Columbia according to the vegetation.

Habitat has been classified according to vegetation in several parts of the United States (Heimburger 1934, Kittredge 1938, Westveld 1951, Daubenmire 1952, 1961, Becking 1954, cited in Becking 1957, Heinselman 1963). In general, however, interest has not been strong. Coile's (1938) critical views discussed earlier seem to express the skepticism of United States foresters, who have preferred other approaches; most United States ecologists outside of forestry have been occupied with other problems.

### Ordination

Gleason (1926, 1939) questioned the reality of plant "associations," and viewed the composition of vegetation as a response to variations in environment and history. The environment, in turn, can be regarded as a continuum, as reflected in the established climatological practice of mapping isotherms, isohyets, and so forth, and in the well-established concept of the soil catena (Bushnell 1942). Curtis and his collaborators (Curtis and McIntosh 1951, Brown and Curtis 1952, Bray and Curtis 1957, Maycock and Curtis 1960, McIntosh 1967, and others) showed that vegetation also is a continuum, although the segments of that continuum are geographically disjunct. They ordered local and regional communities against one or more

phytosociological axes to investigate successional and other community dynamics.

Goodall (1953a, 1953b, 1954) proposed the term "ordination" for the arrangement of vegetational data along axes.

Wiedemann (1929, cited by Bakuzis 1962) arranged the Finnish site-types against theoretical gradients of moisture and nutrients. Eneroth (1931, reviewed by Malmström 1949) and Arnborg (1953) have done the same thing with Swedish site-types (fig. 2).

Westveld and Spurr (Spurr 1952, p. 305) developed a "provisional indicator spectrum" for the northeastern United States, in which the plant species are ordered against a single gradient that ranges from dry-infertile to moist-fertile. A plot value on the scale is the result of the combined species presences. The reality of a single gradient that combines moisture and "fertility" is questionable, but Spurr's purpose was simply to illustrate a concept, and not to provide a working system.

Rowe (1956) discussed considerations in the use of plants as indexes to environmental gradients, and developed a trial "vegetation moisture index" for the Mixedwood Section of Manitoba and Saskatchewan based on the species present and their apparent affinity for moisture. The rank of vegetation moisture indexes on his plots was generally similar to the soil moisture regime of the plants involved, with ranking based on soil and topography.

NUTRIENT SUPPLY

| DEGREE OF MOISTNESS | Poor (Dwarf-shrub series) | Good (Lastrea-dwarf-shrub series) | Rich (Forb-dwarf-shrub series) | Abundant (Forb series) |
|---|---|---|---|---|
| Very dry | *Very dry dwarf-shrub type* | | | |
| Dry | *Dry dwarf-shrub type* | *Dry Lastrea-dwarf-shrub type* | *Dry forb-dwarf-shrub type* | |
| Fresh | *Fresh dwarf-shrub type* | *Fresh Lastrea-dwarf-shrub type* | *Fresh forb-dwarf-shrub type* | *Fresh forb type* |
| Moist | *Moist dwarf-shrub type* | *Moist Lastrea-dwarf-shrub type* | *Moist forb-dwarf-shrub type* | *Moist forb type* |
| Wet | *Wet dwarf-shrub type* | *Wet horsetail-dwarf-shrub type* | *Wet forb-sedge type* | *Wet forb type* |

*Figure 2.--Forest types of northern Sweden, arranged against theoretical ordinates of moisture and nutrients (Arnborg 1953). Each type is defined by its vegetation. In this early case, ordination was simply an aid in classification.*

He concluded that plants can provide useful indexes to environmental gradients if the regional ecology of the species is known well enough.

Hodgkins (1960) tested a vegetation index to loblolly pine site quality for a small area on the Alabama Coastal Plain. He assigned an index value to each of a number of plant species, based on the average loblolly pine site index of the plots on which the species was found, and adjusted the values according to the apparent affinity of the species for soil moisture. The value of a species on a plot was weighted according to its abundance on the plot. The plot means of weighted species values, used in a regression equation, predicted loblolly pine site index with a standard error of only ±2.55 feet.

Of operational interest is the fact that almost all the species used by Hodgkins can be identified year round.

Bakuzis (1959) developed an operational system of vegetation indexes to forest environments in Minnesota, which he called "synecological coordinates." Bakuzis and Hansen (1959) compiled a list of the forest plants of Minnesota, and assigned each species a value for heat, nutrients, and light. Maximum values were 5; minimum, 1. The first approximation values were based mainly on the geographic distribution and the known ecology of the species. For example, a species having its northernmost occurrence on exposed south slopes in southern Minnesota would be assumed to have a high heat requirement for that State and would be given a maximum heat index value. Values for each species then were adjusted if the values of its associates indicated adjustment was appropriate.

The moisture value given to any plot was the average of the moisture values of the species found on it. Heat, nutrient, and light values were figured in the same way.

In developing similar vegetation indexes for the Coastal Redwood Region, Waring and Major (1964) measured available moisture, available nutrients, and solar radiation on plots to assign species values. Correlation between the vegetation moisture indexes of plots and their measured minimum available moisture was particularly strong (r = 0.97). Pluth and Arneman (1965) found Bakuzis' moisture and nutrient ordinates strongly correlated with such soil factors as moisture-holding capacity, silt-plus-clay fraction, and exchangeable potassium.

Site index (fig. 3) and basal area have been related to synecological coordinates (Bakuzis et al. 1962, Waring and Major 1964) as has the abundance of tree reproduction (Bakuzis 1959, Bakuzis and Hansen 1962a). In the Border Lakes District and the Central Pine Section of Minnesota, the moisture and nutrient ordinates combined accounted for 36 percent of the variation in jack pine site index (Frissell and Hansen 1963). Synecological coordinates have also been used in the examination of various other ecological relationships (Bakuzis 1962 et seq., Waring and Major 1964).

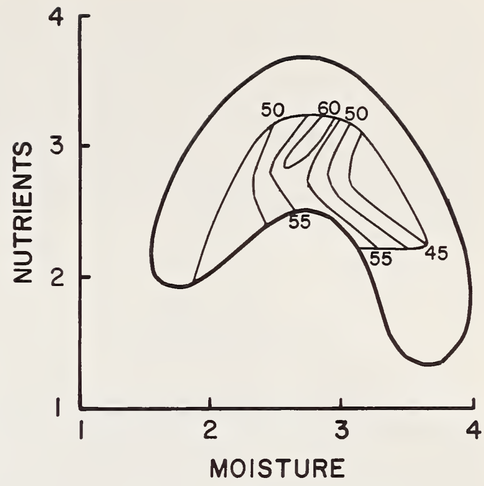


*Figure 3.--Balsam fir site index distribution against phytosociological moisture and nutrient ordinates in the Central Pine Section of Minnesota (adapted from Bakuzis et al. 1962). The heavy outline encloses the set of all forest environments in the section. The lighter outline encloses the set of all forest environments on which balsam fir site indexes were determined.*

On the basis of the limited published work on vegetation ordination, it appears that systems developed specifically for estimating site index may provide quite accurate estimates, while more general systems that can be used for a variety of purposes may not estimate site index very well.

The presence and abundance of each plant species expresses a set of environmental factors more or less unique to that species. A community of plants should express pretty much all of the biologically relevant factors and interactions. Vegetation ordination uses communities to express that

integration of factors more flexibly than classification does. The ways in which plant communities integrate factors are hidden, however, and are relatively unamenable to analysis. It is likely that improved vegetation ordinations will come mainly from aiming ordination at narrowly defined purposes, as Hodgkins did, and from improved index values based on instrumented field studies of species (Cleary and Waring 1969).

### Environmental Approaches

Environmental approaches to habitat evaluation or description are treated here as either factorial or holistic. The factorial approach uses one or more environmental factors believed limiting to the biological process of interest. The holistic approaches subdivide or ordinate the environment as a whole.

#### Factorial Approach

In the section on site index it was pointed out that many locations do not have stands suitable for the direct determination of site index. A natural reaction has been to look for a simple method of approximating site index by relating it to one or more limiting factors. This is the factorial approach, which has been restricted largely to the United States.

Haig (1929), in a pioneering study, used the silt-plus-clay content of the soil to estimate site index for planted red pine on brown forest soils in Connecticut. The approach received increasing attention under the leadership of T. S. Coile at Duke University, beginning with his paper "Relation of Site Index For Shortleaf Pine to Certain Physical Properties of the Soil" (Coile 1935). Scores of studies have since been made for different species and areas; an extensive review was written by Della-Bianca and Olson (1961).

The usual technique can be divided into the following steps:

1. Selection of the environmental factors which might limit or be otherwise related to site index.
2. Selection from among them of factors deemed practical to work with.
3. Definition of a study universe which will restrict as many of the other factors as feasible to a reasonable degree of uniformity. (The importance of this step was not fully appreciated during the early development of the method.)
4. Location of plots in stands suitable for site index determination on habitats sampling the range of variability of the factors being studied.
5. Collection of site index and environmental data.
6. Stepwise regression analysis. The equation to be accepted will include those independent variables that are statistically significant and that also contribute appreciably to the accuracy of the site index estimates.

An alternative to regression analysis is the progressive subdivision of pertinent factor gradients (Gysel and Arend 1953, Strothmann 1960).

Early habitat studies were made in areas of subdued terrain. Climatic variability was restricted by limiting the area included in the study. The Southeastern Section of the Society of American Foresters recently provided a geographic division of a three-State region—Alabama, Florida, and Georgia—into seven provinces and 20 habitat regions based on physiography (Hodgkins 1965). Superimposing a climatic classification, it felt, would provide an excellent framework for studies relating site index to soil and topography.

Different studies have shown different factors to be significant, depending on the species, the factors examined, their intensity range, the manner in which they were measured and expressed, and the statistical and biological relations between the "independent" factors. Nash (1963) points out that "for an independent variable to show partial correlation at a significant level, it must be a variable not a relatively static quantity." He might have added that it must also not be strongly correlated with another independent variable which varies even more harmoniously with site index.

In most studies, soil factors or topographic factors that influence or reflect moisture supply have been important. Examples are studies by Haig (1929), Coile (1935), Gysel and Arend (1953), Young (1954), Weitzman and Trimble (1955), Trimble and Weitzman (1956), Zahner, (1957), Stoeckeler (1960), Cooley (1962), Hebb (1962), Smalley (1964), Carmean (1965), and Kormanik (1966), and in the western United States Carmean (1954), Copeland (1958), Zinke (1959), Myers and Van Deusen (1960), Choate (1961), and Steinbrenner (1965). The factors included soil depth, stone content, soil texture, imbibitional water value of the subsoil, depth to mottling, degree of slope, slope position, aspect, and the concavity or convexity of the slope.

Even without chemical soil analysis, the apparent nutrient regime often seems important. Studying ponderosa pine in the Black Hills, Myers and Van Deusen (1960) found soils derived from limestone to differ in site index from soils derived from crystalline rocks. Yawney (1964) found oak site index in West Virginia to be higher on soils from limestone that on soils from shale and sandstone. Minnesota aspen grew faster on calcareous than on noncalcareous drift (Stoeckeler 1960). In Ontario, Chrosciewicz (1963) found higher jack pine site indexes on glacial drift with a higher proportion of basic minerals, and Heinselman (1963) related forest growth to the mineral status of bog water in northern Minnesota peatlands.

The importance of climate other than microclimate is apparent from several studies. Zinke (1959) found the site index of Douglas-fir and ponderosa pine related to average annual precipitation in northwestern California. Stephens (1965) found that Douglas-fir site index in the Cascade Range in northwestern Oregon varied substantially between different great soil groups, an effect which he said "appears to be associated with climate." Stoeckeler (1960) stated that aspen in the Turtle Mountains of North Dakota grow more slowly than in northern Minnesota because of substantially less precipitation. When Hill et al. (1948) compared similar soils in adjacent counties of Washington, they found that although both received abundant precipitation, the sites with somewhat greater rainfall had a Douglas-fir site index about 30 feet higher than those in the other area. Carmean (1954) also found that Douglas-fir site index increased with precipitation in southwestern Washington. Choate (1961), Hayes and Hallin (1962), and Steinbrenner (1965) all found elevation influential, presumably through its influence on temperature, precipitation, or both. Jack pine site index in Ontario differs from one climatic section to another (Chrosciewicz 1963). Latitude was significantly correlated with the site index of shortleaf pine (Coile and Schumacher 1953) and that of Douglas-fir (Choate 1961), presumably due to changes in temperature and possibly in precipitation.

The suitability of a site index estimating equation usually is evaluated by examining the coefficient of determination or the standard error. These express the overall accuracy of the estimates more or less correctly, depending on how well the distribution of the variables meets certain prerequisites (Ezekiel 1941, p. 16.). Covell and McClurkin (1967) observed that equations for estimating site index from habitat variables seldom account for more than 50 to 60 percent of the site index variance. Their own equation, for loblolly pine on a single soil series, accounted for 63 percent of the site index variance although a wide longitudinal range was included (Alabama to Texas). Myers and Van Deusen (1960) related ponderosa pine site index to habitat factors, for the limestone area and separately for the area of metamorphic rocks, in the Black Hills. Each of their equations accounted for 80 percent of the site index variation. Carmean (1965), working with black oak in southeastern Ohio, developed a different equation for each of two soil textural groups. Like a number of workers, he used a transformation of height as the dependent variable and age as an independent variable. Each of his equations accounted for 80 percent of the variance in tree height, probably due to narrowly and appropriately defined study universes. That is not as good as accounting for 80 percent of the site index, however. . The variance in height was considerably greater than the site index variance would have been, and a large part of it is accounted for by age.

Areas such as the Rocky Mountains of Colorado comprise a complex of environmental variables, many of which have a wide range of variability even within a single cover type. These variables may limit biological behavior in a variety of combinations; many interact ecologically and are confounded statistically. In such an area, the factorial approach by itself seems unlikely to provide a useful estimator of productivity. It has proved useful, however, when used within narrow subdivisions of a regional environment—for example, the two primary geological subdivisions of the Black Hills (Myers and Van Deusen 1960). To divide the Colorado Rockies into units of comparable climatic-geologic homogeneity might require a more formal classification incorporating several criteria—a holistic classification as a framework for the factorial approach.

## Holistic Approaches

In one holistic approach, the environment is classified by classifying the landscape as a whole. That is the basis of the soil survey approach and German site mapping. It is also the working basis of the physiographic site classification of G. A. Hills (1952 et seq.).

Another holistic approach is to develop a theoretical though more or less arbitrary model of the environment, measure or estimate the necessary environmental variables, and incorporate them in the model. This is the conceptual basis of Hills' physiographic site classification. Loucks (1962b) and Jones (1967b) carried it further in ordinating forest environments in New Brunswick and in the Southern Rocky Mountains, respectively.

Holistic approaches will be discussed as (1) soil survey, (2) German forest soil maps, (3) Hills' physiographic site types, and (4) environmental ordination.

**Soil Survey.**[5] —Retzer (1958) criticized the factorial approach as providing only a productivity appraisal. Other purposes would require remapping the management area on other bases. He felt that mapping soil taxonomic units provides a sound general basis for wild land management including productivity appraisal.

A soil is not simply a soil profile with certain characteristics. It is a three-dimensional segment of the landscape with a characteristic profile and shape. Soil surveys divide the landscape into taxonomic units. Available forest soil survey maps are based either on the recent 7th Approximation classification (Soil Survey Staff 1960) or on the preceding classification (Soil Survey Staff 1951). In either case, the basic mapping taxon is the **soil series.** The differences between series are narrow. Series including more than one surface soil textural class may be subdivided into types according to texture. Phases may also be recognized, based on soil depth, stoniness, slope, and the like (Soil Survey Staff 1951). Series are defined and recognized by characteristics of the soil profile that reflect the climate, organisms, topography, parent material, and time (Jenny 1941). Some of the classifying criteria have direct significance to plants, and soil phases are delineated by characteristics important to ecology and land management.

The utility of soil maps in ecology or wild land management depends on whether the units defined are sufficiently uniform ecologically. This in turn depends on the degree of coincidence of the classification criteria with the characteristics of greatest relevance to problems of forest management. Coile (1960), a man of wide experience in relating southeastern soils to forest growth, felt that the coincidence is inadequate, at least for evaluating yield capacity.

The evidence is not conclusive. In most papers only the soil series is given and phases are not differentiated.

Zinke (1961) found ponderosa pine site indexes (index age 300) ranging from 107 to 180 feet on the Underwood series in California; average annual precipitation ranged from 15 to 35 inches. Site indexes on the Shaver series varied from 89 to 182 feet, with average annual precipitation of 12 to 55 inches! Covell and McClurkin (1967) found loblolly pine site indexes ranging from 59 to 105 feet on 89 plots on the Ruston series.

Stoeckeler (1960) found that soil **types** estimated aspen site index fairly closely on his plots in northern Minnesota and northern Wisconsin. The summer climates sampled were not very heterogeneous, however, and he purposely did not sample rough topography or habitats, the site index of which might be influenced by slope or aspect.

Phillips and Markley (1963) presented site indexes (index age 50) for New Jersey sweetgum by soil series. Eight series were represented by at least three plots each. They had the following site index ranges and sample sizes:

| Series | Plots (Number) | SI range (Feet) |
|---|---|---|
| Othello | 3 | 2 |
| Matlock | 3 | 4 |
| Bayboro | 5 | 9 |
| Adelphia | 5 | 9 |
| Rancocas | 5 | 12 |
| Weeksville | 3 | 15 |
| Bustleton | 5 | 21 |
| Keansburg | 10 | 23 |

The authors (pp. 14-16) imply that recognition of drainage phases and water table phases in some series would have improved estimates appreciably.

[5] *In this paper, "soil survey" refers to the classification and mapping of landscapes by the Soil Survey Staff of the U. S. Department of Agriculture and by other public and private agencies using their classification and methods.*

It seems clear that series alone are too heterogeneous ecologically to serve as a basis for evaluating timber productivity, and probably would prove too heterogeneous for other purposes too. Cox et al. (1960) showed the improvement that might be expected in the Rocky Mountains when appropriate phases are recognized.

On the Pacific Coast, series and phases of wild land soils have been mapped (U. S. Forest Service 1954). Types have also been differentiated on some maps (Gehrke and Steinbrenner 1965), presumably when series have considerable textural diversity. Phases are defined not only by ecologically relevant characters of soil and topography, but for some series even by the amount of precipitation (Sauerwein 1965). Three agencies survey wild land soils in California. The U. S. Soil Conservation Service maps soils, while the California Cooperative Soil-Vegetation Survey maps soils and vegetation together, as does the California Region of the U. S. Forest Service (Zinke and Colwell 1965). Vegetation mapping provides a vegetation inventory as well as a classification refinement.

By 1963 over 30 million acres of wild land soils had been mapped in California (Bradshaw 1965). Other large areas, including industrial forests, have been mapped in Oregon (Corliss and Dyrness 1965, Gehrke and Steinbrenner 1965, Sauerwein 1965, Stephens 1965).

The writer has seen no data other than site indexes by which the units delineated by soil-vegetation surveys can be evaluated as ecologically homogeneous units. It seems certain, however, that all the pieces of land on "Q" National Forest designated soil series X phase ab and bearing vegetation type $\frac{\text{OY 321}}{\text{CHy}}$ will be rather similar habitats.

One drawback to soil survey as a habitat classification in forestry is the large and cumbersome number of mapping units—normally series and phases. On 50,000 acres in the foothills and west slope of the Oregon Cascades, 50 different mapping units were recognized (Sauerwein 1965), and on 128,000 acres in the Georgia Piedmont, 73 mapping units were recognized (Byrd et al. 1965).

On the other hand, that multiplicity gives the system versatility. Soil survey classification is not really an ecological classification, but only a basis for one. After the landscape has been classified and mapped, the mapping units must be interpreted for silvicultural or other purposes (Wertz 1966). For example, interpretation data may indicate that the 61 soil mapping units of an area can be grouped into seven sets for the rough classification of timber productivity, and differently into six other sets for prescribing reforestation methods. It then becomes possible to make simpler special-purpose maps from the detailed general map of soil series and phases.

The uses of the soil survey classification of wild lands include not only productivity evaluation, but evaluation of erosion and sedimentation hazards, trafficability, forest regeneration problems, and forest disease and insect problems (Bradshaw 1965, Corliss and Dyrness 1965, Orr 1965, Richlen et al. 1965, Sauerwein 1965).

One might question the use of a primarily pedological classification for wild land management. The classification is based mainly on characteristics that reflect profile development, and are related to forest ecology only indirectly and loosely. The opportunity to include features with specific silvical importance comes only in the recognition of soil phases. Making the maps as useful as they could be by recognizing all the appropriate phases is likely to result in maps that are needlessly hard to interpret. For forestry purposes, pedological mapping might better end with great soil groups or subgroups, which could be subdivided into ecologically defined phases. Much more ecological information could be included in a given number of mapping units.

**German forest soil maps.**—Wittich (1962) described in English the classification and mapping of German landscapes for forestry purposes. A separate classification is made for each "growth district." The first level of classification recognizes genetic soil groups equivalent to "great soil groups" or "little soil groups" in America, and much broader than our soil series. Further classification reflects solely the effects of the soil, parent material, and topography on the forest; the criteria are ecological rather than primarily pedological. The classification is based on examination and interpretation of many soil pits and the associated vegetation and timber. The soil mapping types or "site-units" (Standorts-Einheiten), though defined by soil characteristics, are as uniform as feasible in ground vegetation and timber productivity.

After the classification is complete, topography, vegetation, and stand characteristics are used as guides so far as possible in mapping the district soils, somewhat as in American soil survey. Because the German mapping types are largely eco-

logically defined, however, they probably are more closely related to vegetation and stand characteristics than are American soil phases. This should make them silvically more homogeneous as well as easier to map.

**Hills' physiographic site-types.**—G. A. Hills of Canada developed a "total site" classification. He defined total site as "an integrated complex of climate, relief, geologic materials, soil profile, ground water and communities of plants, animals and man" (Hills 1955, p. 120). Actually it is a classification of the physical environment, and the basic units are physiographic site-types. The vegetation helps to set the physical definitions of the physiographic site-types, however, and aids in field identification (Hills 1955, p. 5), as in the German system. After the sites have been classified, the plant communities on each physiographic site-type are described and their successional dynamics are discussed.

Hills presented his concept and methods in essentially their fully developed form for the first time in 1952, and discussed them further in subsequent papers (Hills 1953, 1955, 1960, 1961a, 1962, Hills and Pierpoint 1960). He recognized the environment as a complex whole, and as a working basis recognized three environmental regimes: climate, moisture, and nutrients. Each is treated separately from the others, but the same environmental elements might be considered in more than one regime. For example, soil colloids are significant to both moisture and nutrient regimes, and topography to both climate and moisture regimes.

Macroclimate is held essentially constant by working within geographic sections, either those of Rowe (1959) or, in Ontario, Hills' own. Within a region, microclimates are classified into 10 levels from warmest to coldest. Assignment to a microclimatic rank is based on topographic situation, air drainage, and presence of a water table at or near the surface.

The other regimes are also subdivided into 10 intensity classes. Assignment to a moisture rank is based on the "pore pattern" of the soil—a function of texture and structure—and on soil depth, topographic situation, and water table. Nutrient rank is based on pore pattern, parent material, and profile development.

In a sense this is an ordination system in which units are assigned ordinates on other than quantitative bases.

As in soil survey and vegetation classification, in Hills' system a habitat is assigned to a classification unit according to the practitioner's judgment. Hills' concept, charts, and tables provide a controlling frame of reference and evaluation aids. Hodgkins (1960), after reading a regional physiographic site-type classification (Bedell and MacLean 1952), concluded that it would be difficult for a mapper to identify all of Hills' site-types with precision because of vagueness and overlapping in some of the site-type descriptions. Rowe (1962), a Canadian himself, wrote:

> The close integration and mutual dependence of all elements at all levels in the classification makes Hills' system difficult to comprehend and to apply by any except those who have worked in close association with him.

Both physiographic site-type classification and soil survey classify the landscape directly, but Rowe (1962) pointed out an important difference. In soil survey the soil profile type is of key importance. In contrast, different profile types occur within the same physiographic site-type. Hills considers profile only within the framework of a land-form classification, and then only so far as it seems relevant to forest dynamics.

Compared to soil survey, physiographic site-type classification of an area results in far fewer, and therefore more inclusive, mapping units. Nonetheless, the units may well be as homogeneous ecologically as those of soil survey because they are delineated entirely by factors that seem ecologically important. Bedell and MacLean (1952) classified approximately 8 million acres (as judged from the map) of a topographically diverse forest section north of Lake Superior. They defined only 16 physiographic site-types. In the larger Clay Belt Section of eastern Canada they differentiated 17 site-types (MacLean and Bedell 1955), while in a 50-million-acre section of northern Alberta, Duffy (1965) defined 12 site-types.

Perhaps this relative simplicity would be less in the mountainous West. A system similar to Hills' was used by Lacate (1965) to classify and map mountain habitats in British Columbia. On 9,800 acres of rugged land with a complex of soil parent materials—tills, colluvium, alluvium, outwash, and lacustrine deposits—he classified and mapped 40 physiographic site-types. Whether that larger

number is entirely the result of greater environmental complexity or to some extent of finer splitting cannot be evaluated from a distance.

Farrar (1962) felt that, for use in the mountainous West, physiographic site classification should consider precipitation in the moisture regime.

Physiographic site-type classification serves several purposes. The units are intended to be approximately homogeneous in timber productivity and successional dynamics, and consequently a good basis for productivity evaluation and silvicultural prescription. Pierpoint (1962) provided an example of the classification of a large area, with complete mapping of site-types and detailed description of vegetation and succession. Physiographic site-types also have served as the basis for land use capability ratings which consider the potential for agriculture, wildlife, and recreation as well as for timber production (Hills 1961b).

For interregional comparisons, Hills' system includes universal as well as regional scales. As it apparently provides no effective way of assigning macroclimatic values, the meaning of such comparisons seems limited.

**Environmental ordination.**—In ordinating environments, one or more environmental gradients are defined. Each ordinate integrates relevant habitat factors by means of a theoretical model and the available data. For example, Thornthwaite and Mather's (1955) annual "soil moisture deficit" is a moisture regime ordinate that integrates experimental data on precipitation, evapotranspiration stress, soil moisture storage capacity. and so forth.

In the Green River drainage of New Brunswick, Loucks (1962b) applied scaling to Hills' environmental regimes. Whereas Hill integrated factors subjectively, using insight and trained judgment, Loucks integrated them using theoretical but defined relationships of factors to one another and to plants. He related the composition and structure of forest communities to the resulting environmental ordinates, or "scalars."

The way in which Loucks constructed his "synthetic moisture regime scalar" illustrates his methods in general. This scalar, which he terms "a first approximation," includes only landscape factors. Precipitation is assumed to be essentially uniform within the area studied, and evapotranspiration is dealt with separately and indirectly outside the moisture regime scalar. The moisture regime scalar is a synthesis of two subordinate scalars. One combines the water-holding capacity of the soil and depth to water table. The other, called the runoff scalar, combines degree of slope and topographic position.

In the Green River drainage, Loucks found that...

> on soils where the prevailing water table occurs within 7 ft of the surface...little or no relationship exists between water-holding capacity and forest composition. This is to be expected, in view of the high precipitation and sustained supply of ground water.

Consequently, water-holding capacity was integrated into the moisture regime scalar only for habitats with the water table below 7 feet. Furthermore,...

> a difference of 1 ft in the depth to the water table in shallow soils results in considerably more change in the vegetation than a difference of 1 ft where the water table is deeper. The gradient is therefore considered to be logarithmic. The range in depth to the water table from zero to several feet can be expressed as a scalar beginning with zero, by adding unity to the observed depth, and using the base-10 logarithm of the sum.

Quoting Loucks again, but deleting citations, the runoff scalar was based on these considerations:

> Two separate [literature] sources indicate that average [storm] run-off, in percent, rises sharply with initial increase in slope to about 18% on a slope of 10%. Thereafter, increase in run-off is more gradual. Average run-off values...at regular intervals of percent slope may then be used to calculate the retention of heavy rains plotted in [Figure 4]. The average fall of rain has been expressed as unity. On a horizontal surface all of it is retained. On a 20% slope 21% is lost in run-off, and assuming little or no replacement at the slope-crest position, 0.79 of the rainfall is retained. Farther downslope, the 21% run-off is added to the unit rainfall; a 21% loss of this total leaves a retention of 0.96. Slopes of 5% gradually come to equilibrium, loss equalling gain. At the foot of the slope, however, an average net run-off of 1% results in an accumulation, the amount depending on the antecedent slopes.

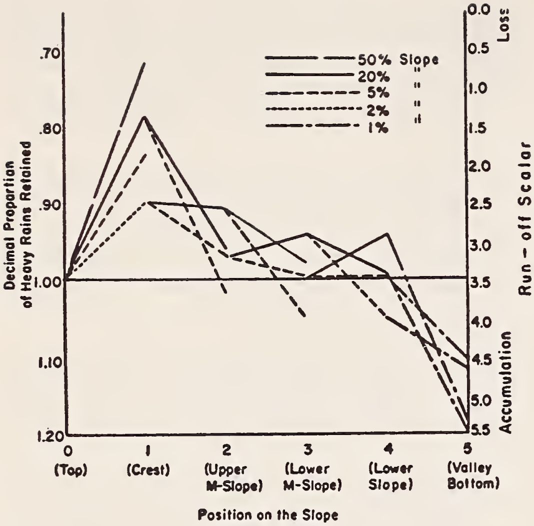


*Figure 4.--Nomogram for a runoff scalar based on slope steepness and position (Loucks 1962b). (Reprinted with permission from Professor Loucks and from Duke University Press.)*

The synthetic moisture regime scalar was then constructed as follows:

> Field observations indicate that on well-drained soils the effects of run-off are only half as important as water-holding capacity. Thus, [in Figure 5,] the slope of synthetic scalar units of equivalent magnitude was established as y = 2x in the area where run-off effects are near neutral and the water table is beyond 7 ft. Because run-off as a moisture factor is negligible where the water table is at or near the soil surface, the slope of the relationship changes gradually from deep to high water tables. Therefore, the original y = 2x slope was extended beyond the upper margin to intersect with the right hand margin of the nomogram, the zero depth to water table. The angle subtended at this intersection by the entire range in run-off and depth to prevailing water table was divided equally into the 10 units of the synthetic Moisture Regime scalar. Thus, proportionately less emphasis is given the run-off component under conditions of a high water table.

The more complex synthetic nutrient regime scalar integrates silt-plus-clay content of the soil, depth of solum, $A_1$ horizon minus $A_2$ horizon, the degree of organic decomposition, and the runoff scalar already mentioned. Parent material was essentially uniform throughout the study area, so it was not included.

The synthetic local climate regime scalar is a synthesis of slope and aspect as they affect daytime temperatures, elevation and topographic position as they influence nighttime temperatures, and the thermal effect of soil moisture as expressed by the moisture regime scalar.

Of necessity, Loucks' pioneer scalars include abundant assumptions and relatively modest supporting data. With them he illustrated a new approach to habitat evaluation, and worked out basic methods. The natural distribution of forest species within the resulting continuum model suggests that even this first model is a reasonable approximation of nature. He did not try to relate site index to it.

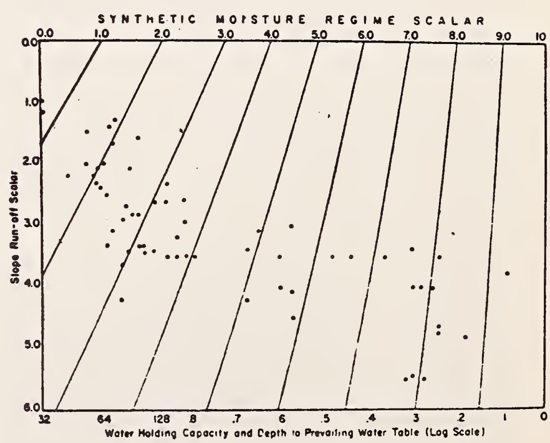


*Figure 5.--Nomogram for a synthetic moisture regime scalar. Positions of samples used in the study are indicated by the dots (Loucks 1962b). (Reprinted with permission from Professor Loucks and from Duke University Press.)*

Jones (1967b) was assigned the development of an equation for estimating aspen site index in Colorado and northern New Mexico from habitat factors. Aspen forest in that region occurs from about 8,000 feet elevation to nearly 11,000 feet, in climatic areas with moisture deficits varying from brief and mild to long. The length and warmth of growing seasons differ substantially. Stands occur on level tablelands and on moderate and steep mountain slopes of every aspect, and on shallow stony soils as well as deep heavy soils. Soils are derived from a wide variety of parent materials. He concluded that the factorial approach was not suited to more than local equations in a region where so many variables might be limiting and in such a variety of combinations. For this reason he turned to ordination.

Moisture regime and temperature regime ordinates were developed. Because of moderate or high site indexes on several plots very low in nutrients, it was concluded that a nutrient regime ordinate was not needed.

The temperature regime ordinate was defined as the total number of degrees by which the average daily maximum temperatures for the months exceeded a threshold temperature. It integrates the length and warmth of the growing season and is analogous to degree-days. The temperature regime ordinates of plots were estimated by a regression equation for the appropriate subregion, with elevation and latitude used as independent variables.

A number of factors were incorporated in the moisture regime ordinate. Multiple regressions were developed from published precipitation records and variables from topographic maps to estimate the normal precipitation of any month for any plot in the region. Other equations were developed to estimate average monthly temperatures, which in turn were adjusted according to the theoretical monthly direct beam insolation as determined by slope and aspect. Thornthwaite and Mather's (1957) tables for estimating soil moisture deficits were used to integrate the effects of estimated normal monthly precipitation, adjusted mean monthly temperatures, and the water-holding capacity of the soil. The latter incorporates soil depth, percentage of the profile occupied by stone, and soil texture. The procedures deviate from those of Thornthwaite and Mather, and the habitats involved fall outside the universe which their tables properly represent. The resulting plot value was therefore regarded as an abstract climate-soil moisture index rather than as an estimate of the soil moisture deficit in inches.

A runoff index was developed to express the effects of runoff inflow and outflow on soil moisture. It incorporated seasonal moisture surplus, the concavity, straightness or convexity of the topographic profile and contour, and the presence or absence of an accessible water table.

The climate-soil moisture index and the runoff index were then combined into a single moisture regime ordinate.

Plots were established to sample the environmental range of aspen stands in the region. The temperature regime and moisture regime ordinates were calculated for each plot, and the multiple regression of site index on the two environmental ordinates was computed. Both partial regression slopes were statistically significant and, combined, accounted for a little more than 30 percent of the total site index variation.

Various assumptions made in constructing the ordinates probably caused much of the unaccounted-for variation in site index. A consideration of aspen genetics, ecology, and sexual and asexual reproduction suggested that another substantial part of the site index variability probably resulted from genetic variability between clones in the Southern Rocky Mountains. Clonal genetic variability was very largely interplot variability, and its effects were therefore confounded with habitat effects. This problem in evaluating aspen sites was discussed by Zahner and Crawford (1965).

As with vegetation ordination, environmental ordination can be either broad and unspecialized, like that of Loucks, or aimed at a specific and narrow purpose, as Jones'. Environmental ordination differs from vegetation ordination in two important ways, however:

1. An environmental ordination reflects how we believe the environmental factors act together to influence plants. Therefore, the success of that ordination is limited by how correct our understanding is.
2. As we improve our understanding of how environmental factors interact to influence plants, we can provide improved environmental ordinations.

So far, environmental ordination is in a primitive stage of development. Theoretically it has much to recommend it, but its actual worth has not yet been demonstrated.

## Summary and Conclusions

Rowe (1962) points out that "purpose is implicit in all classifications and different purposes lead to different classifications." The different backgrounds of different classifiers, and the different climates, terrain, and vegetation of the regions where they work also lead to different classifications. Cajander's (1909, 1926) system of forest site-types resulted from a botanist looking at relatively simple ecosystems in a country with a subdued terrain, a subcontinental boreal climate, and a flora of unusual paucity. Coile's (1938) criticisms of it grew from his experience as a soils scientist in a region of deep soils, very rich flora, and much more diverse secondary succession.

Every approach discussed here seems valid and valuable for some purposes and in some conditions.

So far as forestry is concerned, the primary purposes of site classification or ordination are (1) to identify productivity, and (2) to provide a frame of reference for silvicultural diagnosis and prescription. In the United States to date, most attention has been given to the first purpose—identification of productivity. We have given very little attention specifically to classification or ordination for the second purpose. Systems that might be well suited to the second purpose have been recommended for the identification of productivity instead, and criticized as unsuited to it.

Where it can be used, site index identifies productivity most directly and perhaps best. It is also very useful in the development or application of supplementary and alternative approaches.

The factorial approach can identify productivity satisfactorily when site index cannot be used, providing the equation or table is developed and used in a universe where the limiting variables are neither too numerous nor their relationships too complex. In some physiographic provinces, a factorial site index equation may apply to a rather extensive area. It probably would be necessary to subdivide some other provinces into a number of subprovinces defined by climate, geology, physiography, or some other characteristics, developing a different equation for each.

Vegetation classification, soil (actually landscape) classification, and classification of physiographic site-types have the advantage of being readily used for mapping. For forest management purposes, maps of vegetation types or landscape units have great potential value. Results of silvicultural, pathological, and mensurational research can be referred to the conditions to which they apply, making silvicultural prescriptions, for example, much likelier to succeed. The mapping units by themselves, in some cases, may identify productivity adequately. Where they do not, they would define narrow universes for the simple and accurate use of the factorial approach. Once such maps are available and silvicultural and mensurational research has been correlated with the mapping units, site evaluation and reliable silvicultural prescription often will be primarily a matter of consulting a map, with field checks when desirable.

Detailed soil survey maps—as detailed as those for agricultural land—are becoming available for many areas, particularly in the southeast.[6] In such areas these maps undoubtedly will serve as the primary basis for site evaluation, even though some other approach might have been preferable.

The German approach to landscape mapping seems more appropriate for forestry than does the Soil Survey approach. Where soil survey maps are available, they could make the German approach easier by providing abundant soil information as well as an initial segregation into broad genetic soil groups. The soil-vegetation maps available in some areas would also be useful in the initial correlation of landscape characteristics and vegetation in the German approach.

Hills' approach may also be preferable to that of Soil Survey. It is difficult to compare Hills' approach with that of the Germans. In concept they are very different, but in practice they seem to have much in common. Wittich's (1962) description suggests the Germans subdivide more finely.

Theoretically it should be possible to map synecological or environmental ordinates by entering point values on a map and drawing isolines. Such mapping seems impractical, however, because of gradient discontinuities and reversals. On the other hand, ordination of either vegetation or environment should prove useful in classifying vegetation or landscapes. Ordination can provide a continuum model or coordinate field within which plots can be related to one another by their coordinates (see fig. 3). This can provide a primary basis for deciding what conditions should be included to-

[6] *Letter from Professor Earl J. Hodgkins, Auburn University, Auburn, Alabama to G. Lloyd Hayes, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. June 6, 1968.*

gether in a type for mapping. Vegetation types or landscape units could then be defined initially by the set of ordinates that each includes. More easily recognized criteria would then be developed for field mapping. Determination of ordinates could sometimes help in mapping, particularly in mapping vegetation types under disturbed conditions.

The results of a silvical or silvicultural study are always valid only within certain conditions set by places and times. In appropriately designed field studies, the place (site) can be defined by soil or vegetation mapping units. With environmental coordinates, however, it should become possible to define even artificial environments to some extent, as equivalent to certain field conditions. It should also be possible to state that, because of abnormal weather during a season, the effective environment of a site was approximately normal for coordinate (m, t, n), even though the site is defined as (m', t', n'). Eventually it may become possible to estimate success probabilities for silvicultural treatments at given environmental coordinates.

Environmental coordinates can also provide a basis for the comparison of seed sources in different regions if the coordinate model is valid for both regions.

Factors are integrated into synecological ordinates in an unknown and unadjustable way by the vegetation. On the other hand, satisfactory environmental ordinates depend on our knowledge of ecosystem dynamics. As knowledge increases, environmental ordinate models can be adjusted and refined, which does not seem true of synecological ordinates. Synecological ordinates seem easier to assign in the field, however. Pits need not be dug nor nutrient analyses made.

A case can then be made for a sequence of regional site research (fig. 6).

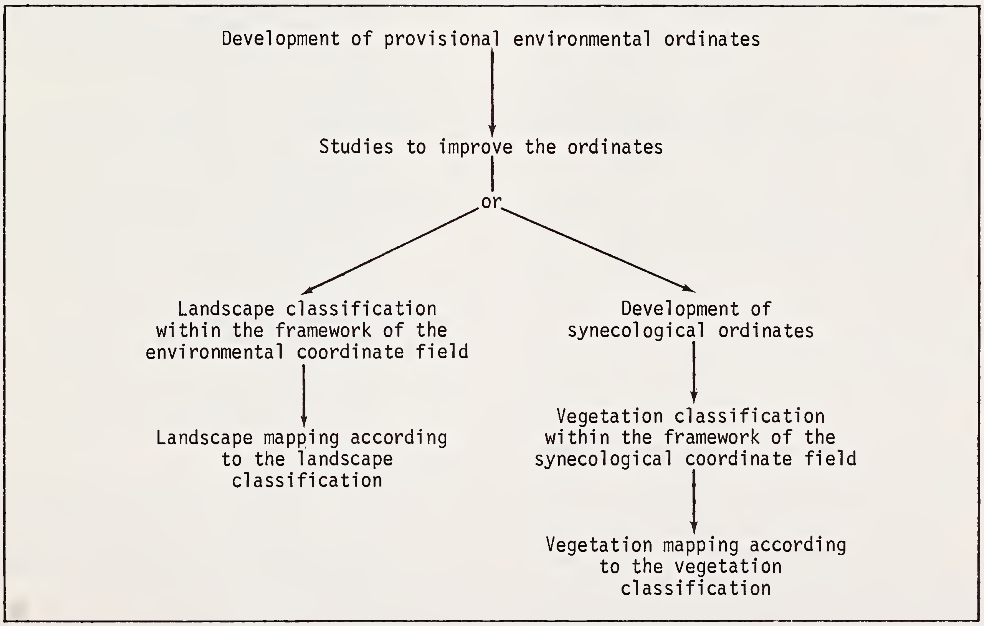


*Figure 6.--Sequence for regional site research.*

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## COMMON AND SCIENTIFIC NAMES OF PLANTS, INSECTS, AND DISEASES MENTIONED

### Plants

| | |
|---|---|
| Aspen, bigtooth | *Populus grandidentata* Michx. |
| Aspen, quaking | *Populus tremuloides* Michx. |
| Birch | *Betula verrucosa* Ehrh. |
| Douglas-fir | *Pseudotsuga menziesii* (Mirb.) Franco |
| Fir, balsam | *Abies balsamea* (L.) Mill. |
| Fir, subalpine | *Abies lasiocarpa* (Hook.) Nutt. |
| Oak | *Quercus* spp. |
| Oak, black | *Quercus velutina* Lam. |
| Pine, eastern white | *Pinus strobus* L. |
| Pine, jack | *Pinus banksiana* Lamb. |
| Pine, loblolly | *Pinus taeda* L. |
| Pine, lodgepole | *Pinus contorta* Dougl. |
| Pine, ponderosa | *Pinus ponderosa* Laws. |
| Pine, red | *Pinus resinosa* Ait. |
| Pine, Scots | *Pinus sylvestris* L. |
| Pine, shortleaf | *Pinus echinata* Mill. |
| Pine, western white | *Pinus monticola* Dougl. |
| Spruce, Engelmann | *Picea engelmannii* Parry |
| Sweetgum | *Liquidamber styraciflua* L. |

### Insects

| | |
|---|---|
| Budworm, spruce | *Choristoneura fumiferana* (Clem.) |

### Diseases

| | |
|---|---|
| Dwarf mistletoe | *Arceuthobium campylopodum* f. *campylopodum* (Engelm.) Gill |
| White pine blister rust | *Cronartium ribicola* Fischer |

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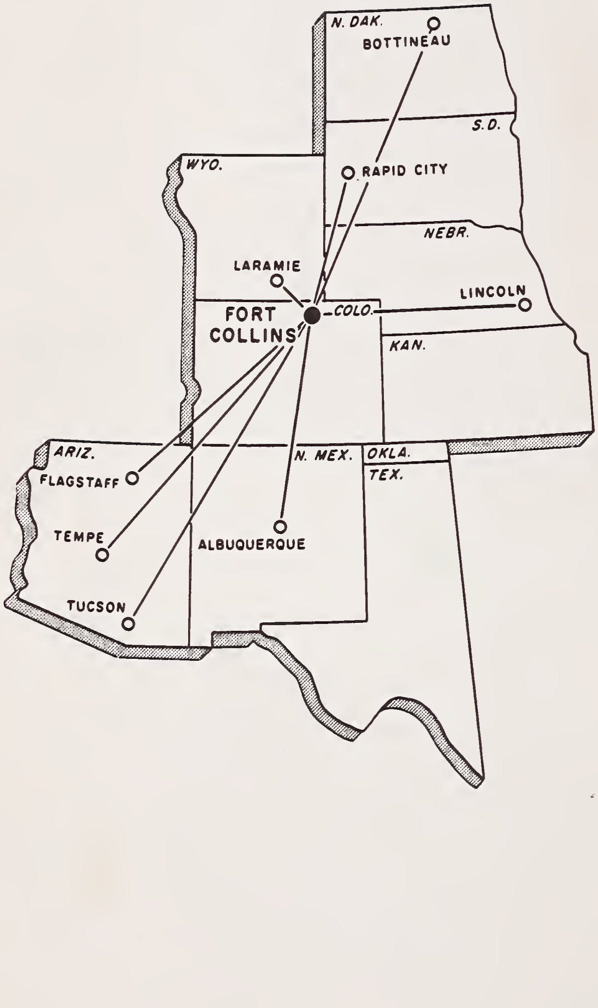
Both the productivity of sites and their characterization for silvicultural purposes are considered. The review covers site index; classification of vegetation site types and physiographic site-types; soil-site equations; classification and mapping of forest soils as done in the United States and Germany; and the ordination of vegetation and of physical environments into gradients representing moisture, temperature, and nutrient regimes. Advantages and limitations of the methods are discussed, and a sequence is suggested for regional site research programs.

Key words: Site index, silviculture, soil mapping, ordination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N. MEX.
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TEMPE
ALBUQUERQUE
TUCSON